Plow-Layer Porosity and Surface Roughness from Tillage as Affected by Initial Porosity and Soil Moisture at Tillage Time[1]

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ABSTRACT

Total porosity increase and random roughness due to plowing were each significantly affected by the moisture content at tillage time. Their magnitudes were greatest at low moisture contents, decreased approximately linearly as soil moisture increased to the lower plastic limit (LPL), and then increased at moisture contents greater than LPL. The porosity before plowing more significantly affected tillage-induced random roughness than total porosity increase. There were significant deviations from these generalities within each of the three so'l associations: Barnes-Aastad, Kranzburg-Poinsett, and Nicollet-Webster.

In all three associations, the porosity decrease by subsqeuent disking and harrowing was more pronounced where plowing gave the greatest porosity increase. Only in the Kranzburg-Poinsett association (high in silt content) were porosity increases observed from disking and harrowing near and above the LPL. Disking and harrowing nearly always reduced random roughness, and the reduction increased linearly as the random roughness of the plow treatment increased.

Additional Key Words for Indexing: soil structure, antecedent porosity, antecedent moisture, soil consistency, infiltration.

Larson has outlined how tillage operations can be analyzed on the basis of the relation between specific soil structural conditions, subsequent microclimatic factors, and a desired soil management objective (8). The concept also provides for evaluation of soil structual conditions in the row zone and interrow zone of a row-cropped field. Two important soil structural measurements of the interrow zone are the plow-layer total porosity and the random roughness of the surface. Both are related to the thermal regime of a soil (15) and to infiltration (5). Field measurement of these two soil conditions has been described earlier (1, 4). The magnitudes of porosity and roughness can be influenced by type of tillage operation, but the effects of soil type, antecedent porosity, and moisture content at tillage time must also be considered.

Information is limited regarding the porosity and roughness as affected by the soil water content at time of plowing (or other tillage). Lyles and Woodruff (10) found the weight proportion of clods > 42 mm produced by tillage of a silty clay loam was the lowest at 0.21 weight fraction of water and increased at greater or lower water contents. This was true not only for moldboard plowing, but also for one way disk plowing.

Lyles and Woodruff (9) observed that cloddiness (as measured by diameter distribution of clods) and draft requirement increased as the dry density of artificially packed soil was increased. These results were obtained using a laboratory chisel type tool drawn across artificial beds of sandy loam, silty clay loam, or clay soil.

Generalization of the relations between soil structural conditions and soil management objectives requires a more comprehensive knowledge of the field variation in soil structural conditions as affected by soil type, soil moisture at tillage time, and initial porosity. This manuscript describes the effect of these factors on plow-layer total porosity and random roughness resulting from moldboard plowing or from subsequent disking and harrowing. The measurements were gathered during four years of field studies on three soil associations in western Minnesota and eastern South Dakota.

METHODS AND MATERIALS

Plow-layer total porosity and random roughness were measured on plow and plow-disk-harrow tillages applied to soils of the Barnes-Aastad soil association near Morris, Minn; the Kranzburg-Poinsett near Madison, S.D.; and the Nicollet-Webster near Lamberton, Minn. The Barnes and Kranzburg are both Chernozem (mollisols) soils, and developed from glacial till and loess, respectively. The Nicollet soil is a Prairie (mollisol) soil and is glacial in origin. The texture of the Ap horizon of all sites in the Kranzburg-Poinsett was silty clay loam; clay loam and predominantly loam in the Barnes-Aastad; and sandy clay loam and predominantly clay loam in the Nicollet-Webster soil association. The greatest textural difference among soil associations was in the sand and silt content (Table 1).

Plowing to a depth of 15 cm was in nearly all sites performed with a 41-cm moldboard, but a 36-cm moldboard was used in a few field sites. In some field sites, the depth of plowing was greater than 15 cm but less than 20 cm, and corrections for depth were made as described later. The speed and plow setting (also that for the disk) was not specifically controlled except that the same operators were involved in all of the tests. Disking and hars rowing was done with a tandem disk having 41-cm notched disk-on the first gang and 41-cm common disks on the second gang; and with a trailing springtooth harrow. In a few instances more

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Table 1—Mean and range for lower plastic limit water content; initial porosity; and sand, silt, clay and carbon contents of Ap horizon observed in the Barnes-Aastad, Kranzburg-Poinsett, and Nicollet-Webster soil associations on which tillage comparisons were made

Measurement	Mean and range for indicated soil associations		
	Barnes-Aastad	Kranzburg-Poinsett	Nicollet-Webster
Lower plastic limit water content, %	25.9 ± 5.0	29.1 ± 2.8	23.5 ± 3.0
Initial porosity, cm*	8.18 ± 0.53	8.59 ± 0.50	7.96 ± 0.83
Sand, %	33.0 ± 12.4	10.8 ± 6.0	40.1 ± 7.1
Silt, %	34.6 ± 5.7	52.0 ± 5.8	28.7 ± 5.6
Clay, %	29.5 ± 10.9	37.5 ± 1.4	31.1 ± 4.0
Total carbon, %	2.95 ± 0.72	2.79 ± 0.54	2.50 ± 0.46

* Initial porosity is the equivalent depth of total pore space in a 15-cm layer of bulk soil.

than one pass with the disk and harrow were made, but this experimental deviation could not be detected in any of the scatter diagrams involving total porosity or random roughness.

No measurements of total porosity and random roughness were made where the tractor wheel traveled during the disking operation. In some field sites, these two tillage treatments were compared side by side, and in others porosity and roughness were measured after plowing and again after disking-harrowing. In all cases plowing and disking-harrowing were performed in the same day, and in most cases the time interval between these tillage operations was less than one hour. About one-half of the tests were made in the spring, and the remaining one-half were made in the summer and fall.

The crop immediately prior to the tillage tests was corn (*Zea mays* L.), alfalfa-brome (*Medicago sativa* L.—*Bromus* L. sp.), oats (*Avena sativa* L.), or soybeans (*Glycine max* L.). Prior to tillage, the growth of alfalfa-brome was usually checked with herbicide. There was some variation in the amount of plant residue left on the plots, but these variations of residue handling could not be detected in any of the scatter diagrams involving total total porosity or random roughness.

Plow-layer total porosity and random roughness were measured by the methods described in (1). Briefly, the total porosity increase was computed from the change in average elevation of the surface observed before and after the tillage operation. The elevation measurement was obtained from heights of pins in a point-quadrant device, and the porosity was represented as the increase in height that resulted from plowing an initial 15-cm depth of soil. In some instances the plowing depth was greater than 15 cm, but the height increases were adjusted to that resulting from plowing an initial 15-cm depth of soil. This adjustment was based on preliminary data showing an approximate 1:1 relation between height increase and depth of plowing when the depth of plowing was varied between 15 and 23 cm. Random roughness is an index of the micro-variation in surface height (1). After correction of the height readings for roughness and slope parallel and perpendicular to the direction of tillage, random roughness was calculated as the standard error of 400 adjusted heights observed on a one-m square area.

Initial porosity (porosity before plowing) was measured using 7.5-cm Uhland cores, assuming a 15-cm depth of bulk soil and a solids density of 2.65 g cm^{-3}. Random measurements of solids density revealed an error of $< 1\%$ in the equivalent depth of porosity due to an assumed solids density of 2.65 g cm^{-3}. An average of at least six 7.5-cm cores was used for each initial porosity determination, and its standard error was < 0.2 cm. Total carbon by dry combustion was determined on a composite of these cores. After H_2O_2 oxidation of organic matter in this composite sample, clay was determined by hydrometer, sand by wet sieving, and silt by difference. Average values and their ranges are shown in Table 1.

The weight fraction of water at the time of tillage was determined from a composite of at least six borings randomly obtained

Table 2—Mean and range of total porosity increase and random roughness observed in the plow and plow-disk-harrow treatments applied to the Barnes-Aastad, Kranzburg-Poinsett, and Nicollet-Webster soil associations

Tillage treatment	Mean and range for indicated soil association and measurement		
	Barnes-Aastad	Kranzburg-Poinsett	Nicollet-Webster
	cm		
	Total Porosity Increase		
Plow	4.96 ± 2.84	4.25 ± 3.01	5.24 ± 2.32
Plow-disk-harrow	3.62 ± 1.99	3.94 ± 3.33	4.29 ± 2.30
	Random Roughness		
Plow	2.83 ± 1.89	2.94 ± 2.24	3.41 ± 2.18
Plow-disk-harrow	1.58 ± 0.77	1.64 ± 0.74	1.92 ± 2.04

from the Ap horizon of each field site just prior to plowing. From the composite of these borings, the weight fraction of water at the lower plastic limit was determined as that water content at which the sample would just roll into a ribbon (2). At least four determinations were made per field site, giving a standard error of about 2×10^{-3} weight fraction of water. For each field site a moisture ratio was determined as the weight fraction of water at tillage time divided by the weight fraction of water at the lower plastic limit. This ratio had a standard error of about 0.02 The range of the moisture ratio was from about 0.5 to 1.2 (see abscissa of Fig. 1), and the range of the lower plastic limit weight percentage of water is shown in Table 1. This normalization of soil moisture at tillage time is based on general soil consistency relations. Abrupt changes of soil consistency occur at the lower plastic limit, and when the texture variation is not large these properties intensify in proportion to the fineness of texture as reflected in the lower plastic limit.

Ninety percent of the variation ($R^2 = 0.90$) in the lower plastic limit weight percentage of water (θ_{LPL}) among sites and soil associations could be explained on the basis of the silt, clay, and carbon contents of the soil as follows:

$$\theta_{LPL} = 4.867 + 0.143\,(\%\ \text{silt}) + 0.235\,(\%\ \text{clay}) + 2.975\,(\%\ \text{C}).$$

Furthermore, the corresponding parameters of the equation for each of the three associations were not significantly different. Each of the parameters in the above relation is significantly ($p < 0.01$) different from zero. The coefficients of the clay and silt percentage show the greater influence of clay than of silt on the lower plastic limit. The coefficient for the clay percentage agrees with that for a Lufkin soil shown by Baver (2), and that for carbon agrees with the values reported by Baver (2) for comparison of virgin and cultivated Putnam soils in Missouri.

Weighted regression analyses were used to represent the relation between the dependent variables, total porosity and random roughness, and the independent variables, moisture ratio, initial porosity, silt, clay and carbon content. The replication for the measurements of the two dependent variables varied from 1 to 9 per field site. Hence, in the regression analyses, the number of replications (trials) per field site was used to weight the dependent variable. This procedure assumed that the inherent variability of all trials was the same. The result is that the site values used in the regression were weighted inversely as their variance. This is a form of weighted regression analysis. The number of field sites is indicated by the number of plotted points in Fig. 1, and the number of trials per field site is indicated in Fig. 1 by different symbols.

RESULTS

The mean and range of the total porosity increase observed within each of the three soil associations for the plow treatment (Table 2) show that the range within a soil association was

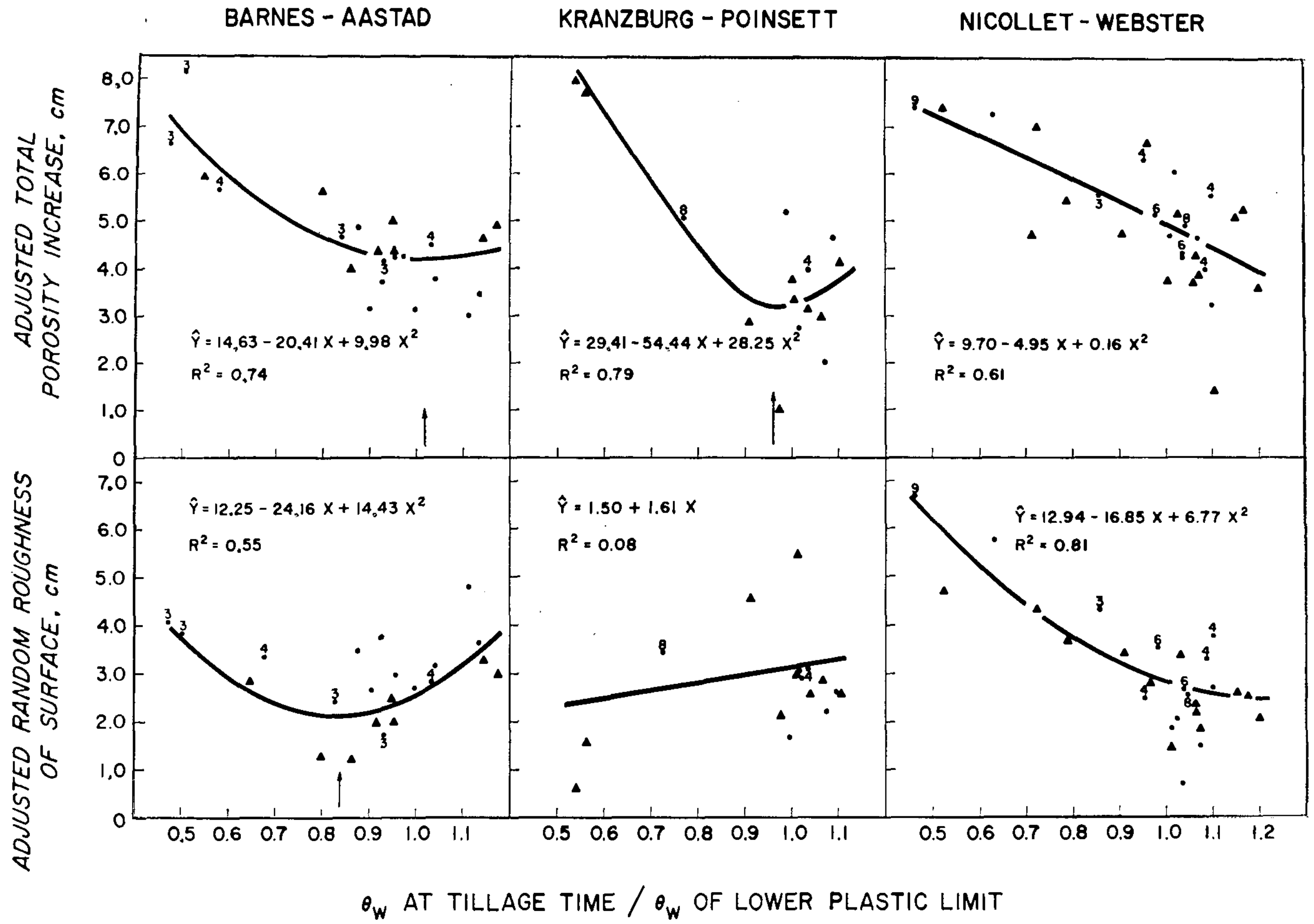

Fig. 1—Relation between adjusted total porosity increase (and random roughness) and the moisture ratio observed in each of three soil associations. (Symbols are used to indicate the number of trals per field site. A dot without a number indicates one trial per field site, a triangle indicates two trials per field site; and those sites having more than two trials are indicated by a number beside the dot.)

greater than the difference of means among soil associations. This was true also for the total porosity increase due to the plow-disk-harrow treatment, and for random roughness within each of the two tillage treatments. For a given tillage treatment and soil association, the range of total porosity increase (and random roughness) indicates that factors within a soil association significantly affected the structure of the plow layer resulting from a given tillage treatment. Two of these factors, moisture content at tillage time and initial porosity, were examined individually for each tillage treatment in each soil association.

Total Porosity Increase and Random Roughness of Plow Treatment

The moisture ratio and initial porosity were the only factors that consistently affected the total porosity increase and random roughness resulting from plowing (Table 3). The significance of an independent variable affecting total porosity increase or random roughness was determined stepwise. As each independent variable was added to the model (proceeding from left to right in Table 3), an increment of regression sums of squares resulted. Using the residual mean square from the full model as a measure of σ^2, the statistical significance of these increments and, therefore, the value of the independent variable was determined. This order of addition of independent variables (other orders of addition could have been used) was chosen from preliminary analysis showing a significant effect of moisture ratio and initial porosity on total porosity increase and random roughness. Preliminary analysis also indicated that the crossproduct term for initial porosity and moisture ratio added little to the accounting for the variation of the dependent variable. Hence, it was not included in the model shown in Table 3. The correlation coefficient relating moisture ratio and initial porosity was always < 0.5 and > 0.

The relation of moisture ratio to total porosity increase and to random roughness was examined more comprehensively by adjusting the dependent variable to the mean level of the remaining independent variables in the multiple regression models of Table 3. These adjusted dependent variables are plotted versus the moisture ratio in Fig. 1 and the equations and R^2 values are from weighted regression of adjusted dependent variable on moisture ratio. As the moisture content at tillage time increased to near the lower plastic limit, the total porosity increase decreased for all three soil associations. At the lower plastic limit and at greater moisture contents at tillage time, there was a greater random variation in the total

Table 3—Multiple weighted regression between total porosity increase (random roughness) of the plow treatment and the moisture ratio, initial porosity, clay, silt, and total carbon content of soils of the Barnes-Aastad (B-A), Kranzburg-Poinsett (K-P), and Nicollet-Webster (N-W) soil associations

Dependent variable†	Soil association	R^2	Intercept	Coefficients in the relation between dependent variable and indicated independent variable‡				
				Moisture ratio	Initial porosity	Clay	Silt	Carbon
Total porosity increase	B-A	0.80	− 86.09	−20.43 }** 10.00 }	31.63 }** − 1.93 }	0.33 − 0.01	0.59 0.01	−17.20 }** 3.21 }
	K-P	0.76	−876.94	−54.14 }** 28.07 }	45.10 − 2.57	43.08 − 0.58	−1.43 0.01	−42.34 7.89
	N-W	0.70	145.85	− 4.95 }** 0.16 }	−50.65 }* 3.15 }	5.56 }* −0.09 }	−0.28 0.01	−10.46 2.34
Random roughness	B-A	0.75	67.87	−24.16 }** 14.43 }	−10.50 }** 0.50 }	−0.04	−0.06	0.05
	K-P	0.65	67.15	49.98 −29.06	−14.54 }* 0.64 }	−0.26	−0.13	3.36
	N-W	0.73	121.99	−16.87 }** 6.78 }	−27.67 }** 1.64 }	0.06	0.27**	− 0.96

† The units of total porosity increase and random roughness is cm.

‡ For each dependent variable and soil association, the upper line is the coefficient of the first degree term and the second line is that for the second degree term. A blank space indicates that the second degree term was not included in the regression. The single and double asterisk , respectively, signify statistical significance at the 5 and 1% level.

porosity increase. The cause of this variation may be the greater number of sites in this region of the scatter diagram. However, it cannot be explained on the basis of previous crop or time of year. In the Barnes-Aastad and especially the Kranzburg-Poinsett associations, there was a tendency for the total porosity increase to increase as the tillage moisture content was increased above the lower plastic limit. This trend was not observed in the Nicollet-Webster association.

For the Barnes-Aastad and the Nicollet-Webster associations, the functional relations of total porosity increase and random roughness versus moisture ratio were somewhat similar. For the Kranzburg-Poinsett association, the random roughness appeared to increase as the tillage moisture content increased. However, the accuracy of the adjusted random roughness versus moisture ratio is doubtful in the case of the Kranzburg-Poinsett association because the regression sums of squares due to the moisture ratio was small and not statistically significant (Table 3).

There was an overall better relation between total porosity increase and moisture ratio than between random roughness and moisture ratio (compare the R^2 values in Fig. 1).

Analogous to the adjustment of the dependent variable in Fig. 1, the dependent variable was adjusted to the mean of all independent variables except the initial porosity. Even though the second order terms were included in the regression in Table 3, the scatter of total porosity increase or random roughness versus initial porosity showed little curvilinearity. The linear relations of adjusted total porosity increase and of random roughness versus initial porosity are shown in Table 4. Within each soil association, the regression of total porosity increase on initial porosity was not statistically significant while the regression of random roughness on initial porosity was statistically significant (compare the R^2 values in Table 4). The slope estimates among soil associations, within each dependent variable, were not significantly ($p < 0.05$) different. Moreover, the range of initial porosities for each soil association overlapped that for the other associations (Table 1). Hence, a linear relationship of total porosity

Table 4—Adjusted total porosity increase and random roughness of plow treatment as affected by initial porosity of 15-cm soil layer of Barnes-Aastad, Kranzburg-Poinsett, and Nicollet-Webster soil associations

Soil association	Dependent variable	Parameters of linear relation with initial porosity		
		Intercept	Slope	R^2
Barnes-Aastad	Porosity increase	6.73	−0.22	0.01
	Random roughness	21.59	−2.29	0.62
Kranzburg-Poinsett	Porosity increase	−2.65	0.92	0.10
	Random roughness	33.29	−3.53	0.65
Nicollet-Webster	Porosity increase	7.35	−0.26	0.01
	Random roughness	14.73	−1.42	0.42
Overall	Porosity increase*	7.71	−0.32	0.02
	Random roughness	16.31	−1.61	0.46

* Because of their qualitative dissimilarity, the estimates for porosity increase in the Kranzburg-Poinsett association were not included with the others in the overall regression.

increase or random roughness versus initial porosity was estimated for all three soil associations lumped together (Table 4). The overall regression shows that increases of initial porosity consistently decreased random roughness. There was also a predicted decrease of total porosity increase as initial porosity increased but the precision of the estimate was poor. This analysis indicates a low precision relation between initial porosity and total porosity increase while Table 3 indicates, for the Barnes-Aastad and Nicollet-Webster associations, a significant reduction in residual sums of squares from addition of initial porosity to the model. This significant reduction was due to inclusion of the second order term, which showed unrealistic curvilinear relations in a plot of total porosity increase versus initial porosity.

If random roughness may be considered as an indication of average diameter of aggregates resulting from plowing, the total porosity increase as affected by initial porosity was not a simple shattering of a dense layer. This problem will be treated in more detail later.

Previous crop and its associated tillage management influenced total porosity increase and especially random roughness at least in part through its effect on initial porosity.

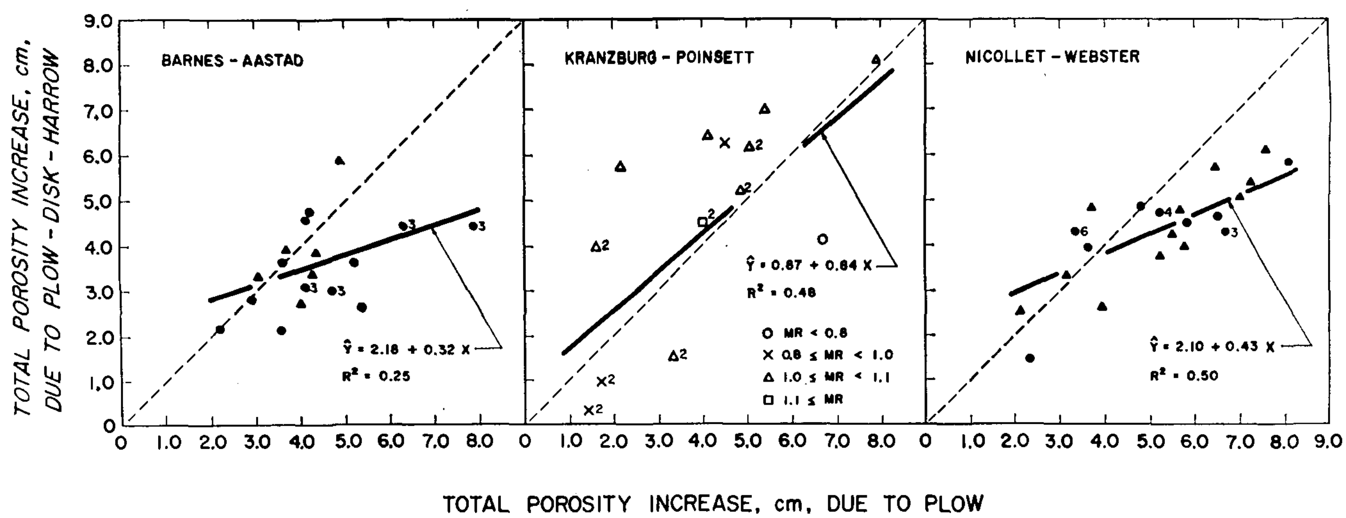

Fig. 2 Total porosity increase in plow-disk-harrow treatment as related to that in the plow treatment in each of three soil associations. (In the Kranzburg-Poinsett association, different symbols indicate the moisture ratio range for the observation; the number beside the symbol indicates the number of trials per field site; and those without a number had one trial per field site. In the Barnes-Aastad and Nicollet-Webster associations, a dot without a number indicates one trial per field site; a triangle indicates two trials per field site; and those sites having more than two trials per field site have a number beside the dot.)

The different previous crops (corn, brome-alfalfa, alfalfa, or small grain) were not distinguishable as separate curves in Fig. 1. However, scatter diagrams (not shown) of adjusted random roughness or total porosity increase versus initial porosity indicated higher initial porosities for corn and small grain than for brome-alfalfa and alfalfa. Associated with these higher initial porosities, smaller random roughness and total porosity increases were observed.

Other than their effect on the water content of the lower plastic limit, clay, silt, and organic carbon exerted no consistently significant effect on total porosity increase or random roughness (Table 3). However, the small range of these independent variables within a soil association (Table 1) does not permit a conclusive test for their effects other than on the lower plastic limit.

Total Porosity Increase and Random Roughness of Plow-Disk-Harrow Treatment

In all three soil associations, the total porosity decrement from disking and harrowing increased as the total porosity of the recently plowed layer increased. Slope values less than 1 in Fig. 2 illustrate this observation. There were instances however, (at lower values of total porosity increase on the plow treatment) where the disk-harrow treatment increased the total porosity of the recently plowed layer. This occurred least frequently in the Barnes-Aastad and most frequently in the Kranzburg-Poinsett association. In the Kranzburg-Poinsett association, where the total porosity modification from disking and harrowing least depended on the porosity of the plowing treatment (a slope of 0.84 vs. 0.32 and 0.43 for the other associations in Fig. 2), the moisture content at tillage also determined whether disking and harrowing modified the porosity of the plow treatment. At moisture contents near and above the lower plastic limit (MR $\geq$ 1.0), disking and harrowing generally increased the porosity, whereas at moisture contents below the lower plastic limit (MR $<$ 1.0) porosity decreases generally resulted from disking and harrowing. This was verified from regression analyses similar to those shown in Table 3. When applied to the Barnes-Aastad and Nicollet-Webster associations, there was no significant relation between moisture ratio and the difference of total porosity increase between the plow and the plow-disk-harrow treatments. However, in the Kranzburg-Poinsett association, there was a significant relation between moisture ratio and the difference of total porosity increase between the plow and plow-disk-harrow treatments.

Table 5—Random roughness of plow-disk-harrow treatment as related to random roughness of surface of plow treatment on Barnes-Aastad, Nicollet-Webster, and Kranzburg-Poinsett soil associations

Soil association	Parameters of linear relation*			
	Intercept	Slope	R^2	Intersection of linear relation and 1:1 line
Barnes-Aastad	0.60	0.34	0.78	0.91
Nicollet-Webster	0.22	0.50	0.70	0.44
Kranzburg-Poinsett	0.80	0.27	0.79	1.10

* The linear relation model was:

$$Y = \alpha + \beta X$$

where Y is the random roughness of the plow-disk-harrow treatment, α is the intercept, β is the slope, and X is the random roughness of the plow treatment. In the regression calculation, Y was weighted according to the number of trials per field site.

Disking and harrowing always reduced the random roughness of the recently plowed surface, and the reduction was greater when the plowed surface was rougher (Table 5). Rarely was a random roughness $<$ 1.3 cm observed on the plow surface. Conversely, it was always greater than the estimated point of intersection of linear relation and 1:1 line shown in Col. 5, Table 5.

DISCUSSION

The relationships in Fig. 1, Table 3, and Table 4 show the importance of soil moisture content and porosity at tillage time as factors affecting the structural conditions resulting from plowing. Even though the same operators were involved in all of the tests, there were undoubtedly variations in ground speed and plow adjustment not involving changes in depth of plowing. The minor influence of these factors agrees with draft measurements. Keen and Haines (7) showed that ground speed and plow adjustment had little effect on draft so long as plow adjustments did not change the depth of plowing. Payne (12) showed only a small linear increase in draft as speed was increased. There were at least three different manufacturers of moldboard plows and disks used in the present study. There were also variations in size of tractor used, especially in the Nicollet-Webster association field sites. It was also shown in Table 2 that the variations of porosity and roughness were as great within as between soil associations. Yet the variations in total porosity increase were significantly related to moisture ratio (Fig. 1), and variations in random roughness were significantly related to initial porosity (Table 4). The qualitative dissimilarity among curves of Fig. 1 for the different soil associations shows too that total porosity increase or random roughness versus tillage moisture content was influenced by some factors that have not been specifically identified in this study.

Repeatedly questions are posed about the changes in soil structural conditions resulting from long-time use of minimum tillage (with few tractor passes in the field) versus conventional tillage (with many tractor passes in the field). In minimum tillage systems, which are only partially tracked (tractor traffic) after moldboard plowing, the total porosity will be greater than in conventional systems, which are usually 80 to 90% tracked at least once during the period from plowing until next year's plowing. The absence of a significant effect of initial porosity on total porosity increase from plowing (Table 4) agrees with the observation that porosity levels immediately after annual repetitions of a given tillage combination (that is, plowing or plowing-disking-harrowing) remained relatively constant after the first year of the treatment even though there were natural decreases of porosity during the ensuing growing season (1). The decrease of random roughness as initial porosity increases (Table 4) and the greater porosity at time of tillage after the first year predict a lower random roughness the second year. However, there would likely be little change in random roughness after the second year because porosity prior to tillage may no longer be different.

The observations reported herein suggest that infiltration in long-time minimum tillage systems may not be modified as much as indicated from short-term experiments. It has been shown (5) that random roughness and total porosity account for at least 75% of the variation in infiltration due to tillage-induced soil structural conditions. There were indications in (5) that the random roughness influence predominated over the influence exerted by total porosity. There is a large difference in porosity between minimum tillage and conventional tillage due to the amount of surface area packed by implement traffic. When infiltration measurements are made on minimum tillage where conventional methods (or sod crops) were used in previous years, these measurements will likely be an overestimate of the value expected from continued minimum tillage. This inference derives mainly from the relation of random roughness to initial porosity. As initial porosity increases after the first year, random roughness will decline. Consequently, infiltration will likely decline somewhat. These observations also suggest that some tractor wheel traffic or other packing may be desirable to maintain surface roughness and infiltration after plowing in the subsequent year.

The general shape of the curves of random roughness versus moisture ratio (Fig. 1) can be examined in terms of published accounts of soil strength-water content relations. As the water content of soils is decreased (at constant initial density) below the lower plastic limit, soil strength increases. This was shown by Taylor et al. (14) with penetrometer measurements, Taylor and Burnett (13) with vane shear strength measurements, and Farrell et al.[4] with tensile strength measurements. (The lower plastic limit and the 1/3-bar suction have approximately the same water content.) Thus, increasing strength is likely the cause for at least part of this increase of random roughness as the water content of soil at tillage decreases. That is, a greater ease of shear and lower tensile strength should produce a granular structure with a greater predominance of smaller aggregates. During conduct of the experiments, visual observation of aggregate size indicated an approximate proportionality between aggregate size and random roughness. The observation (Table 4) of greater random roughness with decreased initial porosity (number of contacts per unit volume and cohesive forces are inversely proportional to initial porosity) qualitatively verifies the proportionality of shear strength (tensile also) and random roughness. The relation of total porosity increase versus moisture ratio (Fig. 1) is not directly related to strength functions because of other controlling factors such as average aggregate diameter, dispersion of diameters, and bridging between aggregates.

Above the lower plastic limit, random roughness remained constant or increased as the water content of soil increased at tillage time (Fig. 1). Greacen (6) showed small changes in shear strength (under normal loading) with increased water content above the lower plastic limit. Likewise Farrell et al.[4] showed only small decreases of tensile strength and unconfined compression strength as moisture content was increased abo e the 0.3-bar suction water content. However, Greacen (6) and Bodman and Rubin (3) showed a significant decrease of voids fraction under normal loading when the soil water content is at or above the lower plastic limit. Hence, increases of random roughness in this region of moisture at tillage are more likely related to plastic deformation resulting in formation of relatively large aggregates more dense than those of the layer to be tilled.

Judging from the results of other researchers, the curves of total porosity increase or random roughness versus moisture ratio (Fig. 1) are likely to have a shape similar to that relating draft versus moisture ratio. For cemented field soils, cohesion and strength increase as the soil dries. Payne (12) observed a linear increase of draft as cohesion was increased. Nichols (11) observed an increase of dynamometer pull when unconsolidated soil materials were slightly wetter than the lower plastic limit. This was due to adhesion and friction forces between soil and moldboard.

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More comprehensive evaluation of these suggested relations of total porosity increase and random roughness with soil strength functions (and aggregate diameter distributions) should improve significantly our understanding about tillage-induced soil structural conditions. This understanding may then be utilized to produce specific structural conditions necessary to achieve a desired management objective.

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